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Unexpected groundwater recovery with decreasing agricultural irrigation in the Yellow River Basin

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ABSTRACT

Groundwater is an important water resource for agricultural irrigation and industrial and domestic uses around the world, especially in arid regions. China's Yellow River Basin (YRB) is a typical arid and semiarid area where agricultural irrigation depends greatly on groundwater storage. In the YRB, a few ecological restoration projects, such as the Gain for Green project, reduced crop land over 6% around the year 2000, consequently leading to a decline in the groundwater withdraw for irrigation. A few studies emphasized the impact of land use and land cover change on evapotranspiration, soil moisture, and surface runoff processes; however, little is known about the groundwater recovery at the basin scale. In this study, we utilized multiple data sets, including satellite remote sensing (i.e., the Gravity Recovery and Climate Experiment, GRACE), ground observation, and simulation data from land surface modeling, to identify the trend in groundwater storage (GWS) and the roles of climate change and human activities during the period of 2005–2013. The results indicate that there was a consistent estimate for the GWS changes using GRACE and ground observations at the basin scale, indicating a substantial decrease at a rate of about −3 mm/yr. Agricultural irrigation accounted for 61.69% (6.15 mm/yr) of the total groundwater consumption, decreasing by 12.6% from 2005 to 2012. However, the groundwater consumption for industrial, domestic, and public sectors increased, and total groundwater consumption was maintained a stable level of about 10 mm/yr. Therefore, groundwater storage did not recover despite the increased groundwater recharge and the decreased groundwater irrigation. To ease groundwater depletion, groundwater management should be concerned with water allocation for agricultural irrigation and also with industrial and domestic uses, emphasizing water saving and recycling techniques.

1. Introduction

With increasing challenges regarding the availability and reliability of water resources in recent years, it is important to understand issues related to hydrological processes, water supplies, water-use sectors, and management strategies at regional scales (Oki and Kanae, 2006; Schlosser et al., 2014). Groundwater is a vital source of fresh water for its ubiquity, ease of development with minimal costs, and good quality (Hu et al., 2017; Zhu et al., 2017). It will become the ultimate source of water when surface water sources have been depleted, especially for areas with less available surface water areas, such as South Africa, the central USA, Pakistan, and North China (Hanasaki et al., 2008). Groundwater depletion will not only threaten water supply (Schwartz and Ibaraki, 2011) and food security, but also have devastating effects on ecosystems by reducing base-flow to streams and wetlands (Stromberg et al., 1996). In addition, groundwater released from storage will lead to land subsidence and sea-level rise (Konikow and Kendy, 2005).

Groundwater dynamics for most river basins are primarily driven by climate change and human activities (Vorosmarty et al., 2000). Global warming likely accelerates the water cycle of the earth system and, consequently, leads to changes in precipitation and evapotranspiration rate that will lead to a corresponding variation in groundwater recharge (Yu et al., 2017). Besides the diffuse rain-fed recharge, natural groundwater recharge also occurs because of surface water leakage. Therefore, recharge is highly dependent on the prevailing climate as well as on land cover and underlying geology. However, compared with climate change, population growth and economic activities may be stronger drivers in altering groundwater systems in some regions (Dai et al., 2016; Schlosser et al., 2014).

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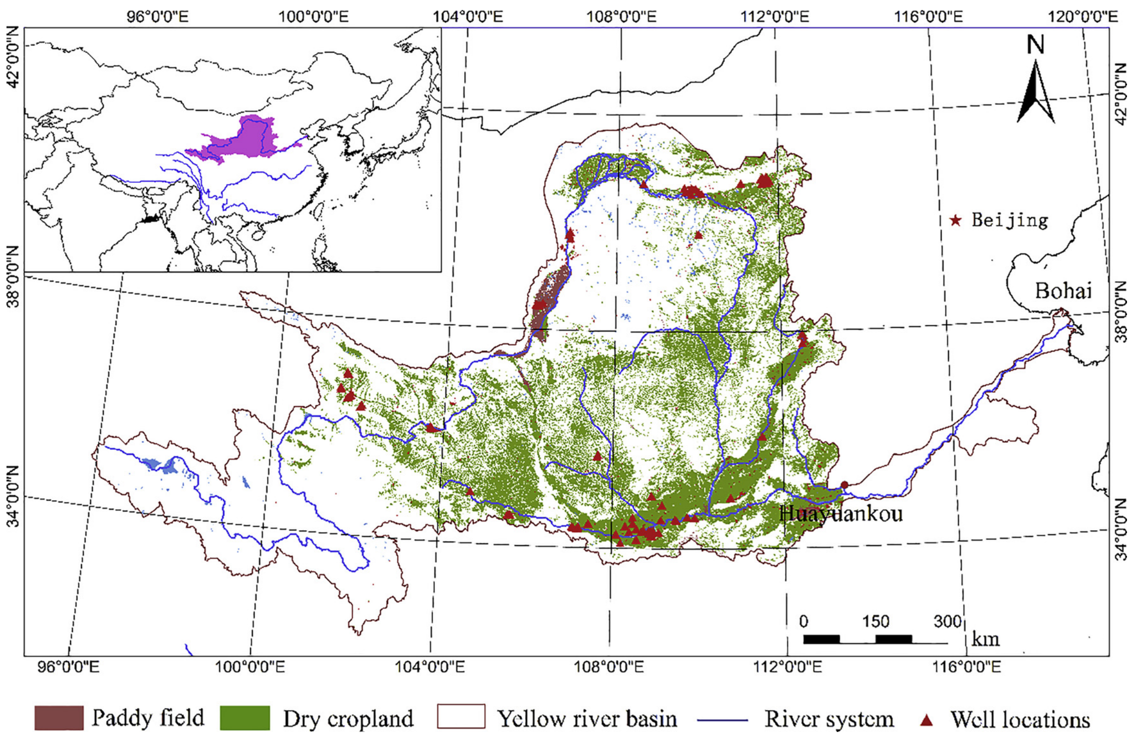

Fig. 1. Locations of the YRB and its crop land distribution, and in-situ groundwater observations.

Groundwater is an important source for domestic needs, industrial production, and agricultural irrigation. About 600–1100 km^3 (20%-33% of terrestrial available water) groundwater is abstracted every year. It is estimated that about 2.5 billion people rely on groundwater as drinking water in the world (Shah et al., 2007). Groundwater contributes to 40% of total industrial water withdrawals and to 50% of total municipal water withdrawals (Zektser and Everett, 2004). Moreover, 38% of the agricultural area (301 million ha) is irrigated by groundwater, accounting for 43% of the total consumption of irrigation water (Siebert et al., 2010). However, demands for non-agricultural uses are also increasing, which have put irrigation water under greater scrutiny (Hanjra and Qureshi, 2010).

China is facing a serious water resource shortage. Groundwater has become a major water source due to the lack of surface water, with more than 40% of farmland irrigated by groundwater and 70% of the drinking water coming from groundwater for the northern and northwestern regions (Hu et al., 2016). An additional 2.5 km^3 groundwater per year has been used to meet these demands (Qiu, 2010); therefore, groundwater in north China, including the Yellow river basin (YRB), has been over-exploited (Liu and Xia, 2004; Xia et al., 2007; Yu, 2006). The Yellow River is the second largest river in China. About 130 million people rely on the Yellow River water supply in northwest and north China (Campos et al., 2003). Agricultural water is the primary usage in the Yellow River basin (YRB), accounting for over 60% of the total water usage (Xu et al., 2011). Annual water withdrawal and consumption is increasing significantly, correlated with the expansion of industrial and domestic demands (Liu and Xia, 2004).

In order to alleviate water scarcity and groundwater depletion in the YRB, water conservation and water-saving practices have been applied in the irrigation districts. Measures include upgraded irrigation scheduling, land levelling of irrigated fields, and improved furrowed and flat basin irrigation systems (Deng et al., 2006). A few ecological restoration projects have been carried out across the YRB, including the Three-North Shelterbelt program, the Gain for Green project, and the shelterbelt program for the middle reaches of the Yellow River (Lu et al., 2018). These projects may have substantial impact on hydrological cycle, including surface runoff generation and groundwater recharge and discharge (Wang and Hejazi, 2011; Xie and Cui, 2011). Moreover, the expansion of these projects shrank the area of arable land and, consequently, reduced the demand for groundwater irrigation. Studies have been published primarily concerned with the surface water hydrology regarding surface runoff generation, the patterns of streamflow, and estimation of evapotranspiration (Chen and Liu, 2007; Li et al., 2014; Xie et al., 2015; Zhao et al., 2009). However, the response of groundwater storage to climate change and the human activities is still unclear, partly due to the limitation of data associated with the groundwater system at a basin scale.

In this study, we employed multi-source data sets from remote sensing, ground observations, and land surface modeling to identify the groundwater dynamics in the YRB. Two questions are expected to be answered. (1) Has the groundwater storage recovered with the reduction of arable land? (2) What were the roles of climate change and groundwater withdrawal on the groundwater dynamics? We focused on the period of 2005–2013 due to data availability and because most ecological restoration projects were been implemented before this period.

In Section 2, we describe the data sets for the YRB and the methods used to compute groundwater anomalies and groundwater recharge. Section 3 includes the results regarding changes in groundwater storage and the contribution from climate change and human groundwater withdrawals. The trends for groundwater storage and contributions are evaluated based on different sources of data. Section 4 discusses the findings and provides potential strategies for water resource management. Finally, the conclusions from this study are summarized in Section 5.

2. Data and methods

2.1. Study area

The Yellow River originates in the Bayangela Mountain, wanders through the northern semi-arid region across the loess plateau, passes through the eastern plain, and finally discharges into the Bohai Gulf (Shao et al., 2009). It flows across nine provinces and supplies water to

about 9% of China's population, mostly farmers and people living in rural areas (Pereira et al., 2007). This study focused on the upper and middle regions (Fig. 1) accounting for 97% (730 000 km^2) of the total YRB. The temperature and precipitation decreases gradually from the southeast to northwest. The long-term average temperature ranges from above 14 °C to below −4 °C. The average annual precipitation ranges from 300 mm to 700 mm, the majority of the annual precipitation occurring from June to September (Liu and Xia, 2004). The area of arable land is 12.6 million hectares, mainly distributed in the central and southern regions of the YRB, and 5.06 million hectares is irrigated (Wang et al., 2004). Irrigation water comes mainly from the river system and groundwater reservoirs.

Due to the climatic condition, agricultural irrigation is essential during the entire growing season. However, the arable land was reduced 1984 km^2 around the year 2000, partly due to the ecological restoration projects (Xie et al., 2015), and this was expected to decrease the groundwater withdrawal to some degree. However, the YRB is facing the dilemma of increasing municipal and industrial water demand, while at the same time maintaining enough in-stream flow for scouring sediment and environmental requirements. The considerable hydrological and climatic uncertainties further increased the vulnerability of the water supply in the YRB (Yu, 2006). Water authorities struggled to balance the demands of various water-use sectors and the supplies from the surface and groundwater storage.

2.2. Data

We used multiple data sets, including satellite remote sensing data, simulation data from a land surface model, and ground-based measurements as shown in Table 1. The satellite remote sensing data were from the Gravity Recovery and Climate Experiment (GRACE). The GRACE satellites monitor temporal variations in the Earth's gravitational potential, which can be interpreted as variations of terrestrial water storage at monthly to inter-annual timescales (Landerer and Swenson, 2012; Reigber et al., 2005; Tapley et al., 2004). Combined with hydrological modeling or other observations, groundwater storage (GWS) can be calculated by isolating other components from the terrestrial water storage (TWS) (Feng et al., 2013). GRACE data can be freely accessed from three different processing centers: Geoforschungs Zentrum Potsdam (GFZ), Center for Space Research at University of Texas, Austin (CSR), and the Jet Propulsion Laboratory (JPL). The GRACE data that we used was the level 3 Release-05 (RL05) from January 2005 to December 2013. To reduce data uncertainties, we averaged the data from the three centers to make a consistent GRACE TWS anomaly.

To evaluate the GRACE estimates of regional GWS changes, the ground-measured data for the monthly average groundwater depth for the same period were acquired from China Groundwater Level Yearbook for Geo-environment Monitoring (Institute of China Geological Environment Monitoring, ICGEM, 2013). As shown in Fig. 1, there were a total of 75 observational wells, including 54 unconfined, 19 confined, and 2 mixed wells. The observation records from the 75 wells were used to represent the variations of the groundwater depths for the YRB.

To identify the contributions of climate change, human activities, and their combined influence on GWS, we also used simulation data produced by Xie et al. (2015) based on the Variable Infiltration Capacity (VIC) model (Liang et al., 1994; Liang and Xie, 2001). The simulation data refer to the soil moisture, precipitation, evapotranspiration, surface runoff and base flow, and these data have been extensively evaluated by Xie et al. (2015). The surface water storage in major reservoirs and net groundwater withdrawal data were accessed from the Water Resources Bulletin for the YRB (WRB-YRB).

2.3. Groundwater storage anomalies

The GRACE data used provided the terrestrial water storage (*TWS*) anomalies. In order to obtain the groundwater storage (*GWS*) anomalies, other parts of the water storage, including soil moisture storage (*SMS*), surface water storage (*RESS*), and snow water equivalent (*SWES*), must be subtracted from the *TWS* anomalies. Groundwater storage changes were be computed as

$$\Delta GWS = \Delta TWS - \Delta SMS - \Delta SWES - \Delta RESS \tag{1}$$

The *GWS*, *SMS*, and *RESS* changes accounted for the majority of the *TWS* changes in the YRB at monthly or longer time scales, so the *SWES* was negligible in this study (Huang et al., 2015).

To evaluate the groundwater storage from Eq. (1), the *GWS* anomalies were calculated based on the ground observations by multiplying ground-measured GW-level anomalies (deviation from the multi-year mean) by a constant specific yield (μ). The values of μ were prescribed based on (Li, 1999), representing the area-weighted specific yield. Changes in *GWS* were calculated as

$$\Delta GWS = \Delta H \times \mu \tag{2}$$

In this study, the water storage anomalies estimated from both GRACE and in-situ ground measurements were represented as the anomalies of equivalent water height. Despite the uncertainties in estimating the changes in *GWS*, Eq. (2) gave a good approximation of the *GWS* dynamics and was used successfully in a few studies (e.g., Feng et al., 2013; Huang et al., 2015; Zhu et al., 2018). A brief discussion on the uncertainties is provided in Section 4.3.

2.4. Groundwater budget

Groundwater recharge is defined as the addition of water to an aquifer or the addition of water from the overlying unsaturated zone or surface water body (Scanlon et al., 2006). Diffuse recharge refers to areally-distributed recharge, such as from precipitation or irrigation over large areas; whereas, focused or localized recharge refers to a concentrated recharge from surface topographic depressions, such as streams, lakes, and playas (Haile, 2011). Recharge to aquifers is complex and dependent upon the climatic conditions, land use, irrigation, and hydrogeological heterogeneity (Arnold et al., 2000). The direct estimation of groundwater recharge at a basin scale is difficult because of the spatial heterogeneity of the soil profile. Here, we used a water balance equation to approximate the groundwater recharge (*R*e, mm/

Table 1
A summary of the datasets used in this study.

Description	Platform	Resolution	Data sources
Terrestrial water storage (TWS)	GRACE	Monthly, 1-deg	https://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land/
Groundwater Table	Observation wells	Daily, point-scale	China Groundwater Level Yearbook for Geo-environment Monitoring
Groundwater consumption	Observations	Yearly, basin-scale	Yellow River Water Resources Bulletin
Precipitation	Tilting rain gauge	Daily, 0.25-deg	http://data.cma.cn/
Soil Moisture	VIC simulated	Daily, 0.25-deg	Xie et al. (2015)
Surface Runoff	VIC simulated	Daily, 0.25-deg	Xie et al. (2015)
Baseflow	VIC simulated	Daily, 0.25-deg	Xie et al. (2015)
ET	VIC simulated	Daily, 0.25-deg	Xie et al. (2015)

yr)

$$Re = Pre - ET - R - \Delta SMS \tag{3}$$

where *Pre* denoted monthly precipitation (mm/yr), *ET* was evapotranspiration (mm/yr), *R* was surface runoff (mm/yr), and *ΔSMS* was the change in soil moisture storage (mm/yr). These variables could be estimated from the VIC modeling (Xie et al., 2015). Note that ΔSMS was the soil moisture from the top two soil layers. In the natural groundwater budget, the groundwater connection in this region with others was not considered in this study, because the study area can be assumed as a close and independent basin, but the groundwater withdraw from this to other regions was included in the groundwater balance. At a yearly scale, the groundwater balance could be expressed as,

$$\Delta GWS = Re - Baseflow - NGW \tag{4}$$

where *ΔGWS* was the change of groundwater storage; *Baseflow* was the baseflow runoff, which can be estimated from the VIC modeling; and *NGW* was the net groundwater withdrawal, calculated by subtracting the infiltration (to the groundwater storage) and the return flow (to river systems) from the total groundwater abstraction (Doll et al., 2012). The term, net groundwater withdrawal (*NGW*), is used interchangeably with groundwater consumption in this study. The data for *NGW* from the WRB-YRB have been well evaluated and widely used in basin-scale water resource assessments in China.

3. Results

3.1. Change in terrestrial water storage

We first detected the change in TWS. In this study, a 13-point moving average was used to smooth the seasonal variations and remove the high-frequency signals contained in the monthly time series to detect the long-term changes (Scanlon et al., 2012). The TWS obtained from GRACE have been intensively evaluated using the data from the Global Land Data Assimilation System (Ni et al., 2014).

As shown in Fig. 2(a), the TWS had a general depletion at a rate of -2.33 mm/yr, and included distinct seasonal and annual fluctuations. During the period from 2005 to 2013, there were three declining periods: 2005–2007, 2008–2009, and 2010–2011, with a significant reduction of about 25 mm occurring in the first period. The *TWS* reached a minimum and maximum in the spring and autumn, respectively. This was mainly due to limited precipitation and agricultural irrigation withdrawal in the spring and the rainy season from July to November. Actually, the variation of *TWS* was closely related to climatic conditions, since it agreed well with the phases of precipitation (Zou et al., 2013).

The spatial distributions of *TWS* were not uniform over the YRB. The *TWS* appeared to be slowly increasing in the source region of the YRB and decreasing over the lower section of the YRB. Fig. 2(b) presented the spatial distribution of the TWS trend. For its upper region, from 2003 to 2010, the *TWS* increased with a rate of about 8.0 mm/yr; but for the middle and lower regions, it substantially decreased at a rate of −7.0 mm/yr. These results were roughly consistent with the estimates in Zhao et al. (2015). This significant decrease was attributable to agricultural irrigation (Chang et al., 2014).

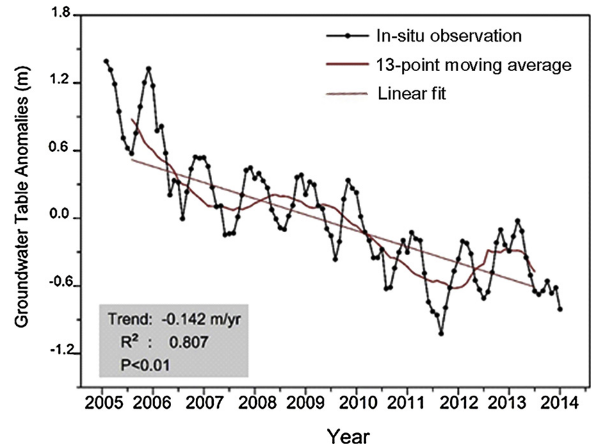

Fig. 3. Temporal variation of groundwater table across the YRB derived from the in-situ observations.

3.2. Trend in groundwater storage

With the decline of the terrestrial water storage, the groundwater system gave a relevant response, characterized by the pattern of the groundwater table and the groundwater storage. Fig. 3 shows average groundwater table variations calculated from the in-situ observations. The groundwater table decreased about 1.28 m from 2005 to 2013. As shown in Fig. 4, the groundwater storage from the in-situ observations had a continuous decline at a rate of −2.85 mm/yr ($P < 0.05$). A similar pattern was also exhibited by the GRACE *GWS* anomaly. The *GWS* depletion rate derived from GRACE was −3.11 mm/yr ($P < 0.05$). Therefore, the GRACE-derived *GWS* agreed approximately with the in-situ observations. However, the former had a larger fluctuation with respect to frequency and amplitude. This difference could be attributed to the sparse in-situ observations of groundwater table and the specific yields that were used to estimate the GWS.

GWS also had obvious spatial variability as a consequence of climatic condition and human activities. Fig. 5 presents the spatial

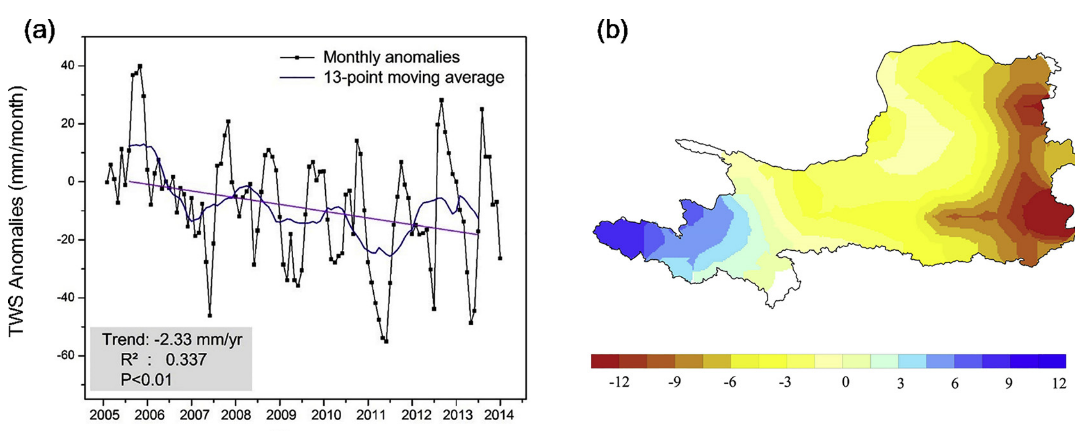

Fig. 2. Terrestrial water storage (TWS) variation derived from GRACE: (a) the average TWS for the entire YRB, and (b) the spatial distribution of the trend of the TWS.

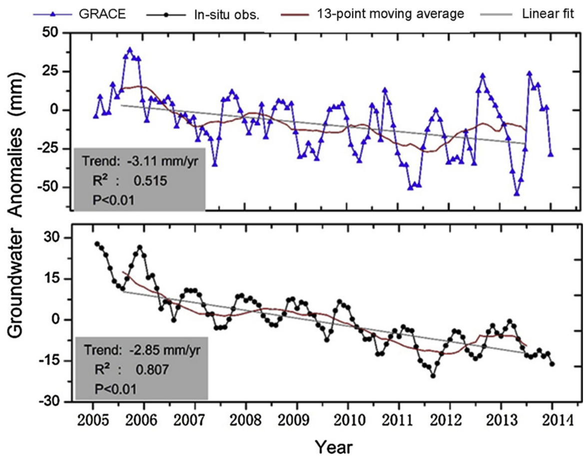

Fig. 4. Groundwater storage variations derived from GRACE and in-situ Observations.

distribution of yearly *GWS* for the period of 2005–2013. Roughly, *GWS* showed an even spatial distribution in the year of 2005, but its spatial variability enlarged over time. In 2009, *GWS* reached negative departures of about −6 mm in the southeastern part of the region, and, after that, the spatial pattern varied to some degree. In the eastern part of the region, a negative anomaly with a maximum of −10 mm was found after the year of 2009, indicating that this region experienced substantial groundwater storage depletion.

3.3. Groundwater budget analysis

A groundwater budget is driven generally by groundwater recharge, baseflow, and groundwater abstraction. Groundwater recharge is dominated by precipitation input, ET, and surface runoff output as expressed in Eq. (3). Here, we analyze each groundwater budget component and further discuss groundwater depletion.

As shown in Fig. 6, annual precipitation increased in the central area of the YRB at a rate of about 20–30 mm/yr from 2005–2013. This increased water input was mostly balanced by the water output of ET and surface runoff, and the groundwater recharge showed an obvious increase in the northeastern area. However, a large decrease of annual precipitation (about −30 mm/yr) occurred in the southeastern area. Consequently, the annual groundwater recharge of the entire YRB was about 56 mm with an upward trend of 0.135 mm/yr (Fig. 7), but it exhibited a slight downward trend in the southeastern area. Along with the variation of the annual groundwater recharge, annual groundwater discharge (baseflow) was about 52 mm, showing a similar temporal trend. From 2005–2013, the net yearly groundwater abstraction by human activities was maintained at a stable level of about 10 mm. This abstraction exerted considerable pressure on groundwater consumption.

The groundwater withdrawal exhibits obvious spatial variability in YRB. Fig. 8 presents the spatial distribution of the groundwater abstraction at province scale for three typical years, 2005, 2010 and 2013. The eastern part of the YRB has quite larger abstraction than the western part. Particularly, the province in the southeast of YRB (i.e., the Henan province) reaches the largest groundwater abstraction, 62.38 mm/yr for the year of 2013. In contrast, the Qinghai province in the west of YRB shows very small groundwater abstraction, 0.74 mm/yr for the year of 2013. The spatial distribution of groundwater abstraction and the groundwater recharge as analyzed above contribute to the groundwater storage decline in the eastern part of YRB.

We calculated the annual groundwater change by two methods, the GRACE-derived groundwater anomaly (i.e., Eq. (1)) and the water balance equation (i.e., Eq. (4)). As presented in Fig. 9, the two methods gave approximately equal estimates for the groundwater change, −3.57 mm/yr and −4.12 mm/yr, respectively, although the GRACE-derived groundwater change showed larger fluctuations than did that

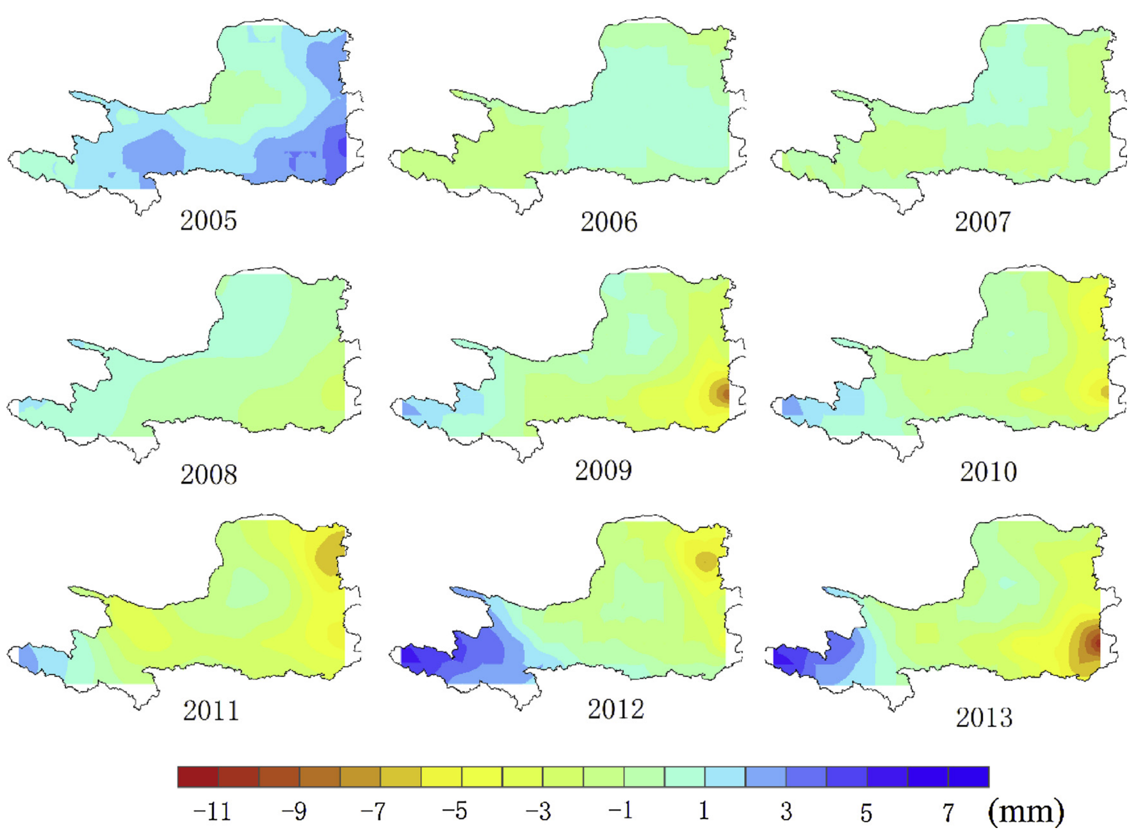

Fig. 5. Spatial variability of groundwater storage in different years.

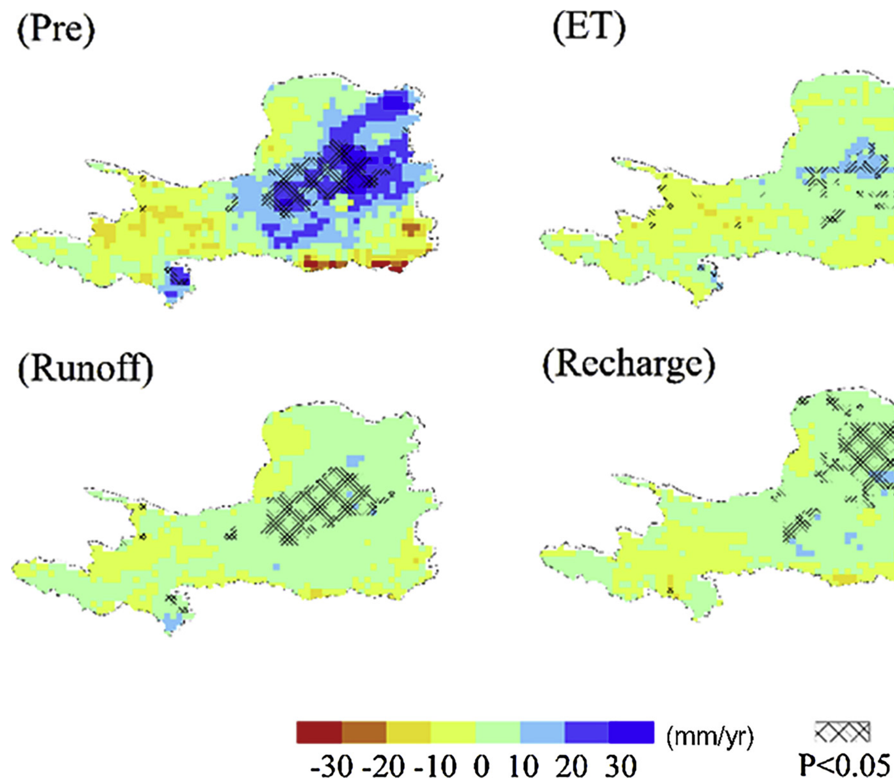

Fig. 6. Trends of precipitation (Pre), ET, runoff and recharge (Re) during 2005–2013. The black cross on the grid denotes the significance level ($P < 0.05$) ($P < 0.05$).

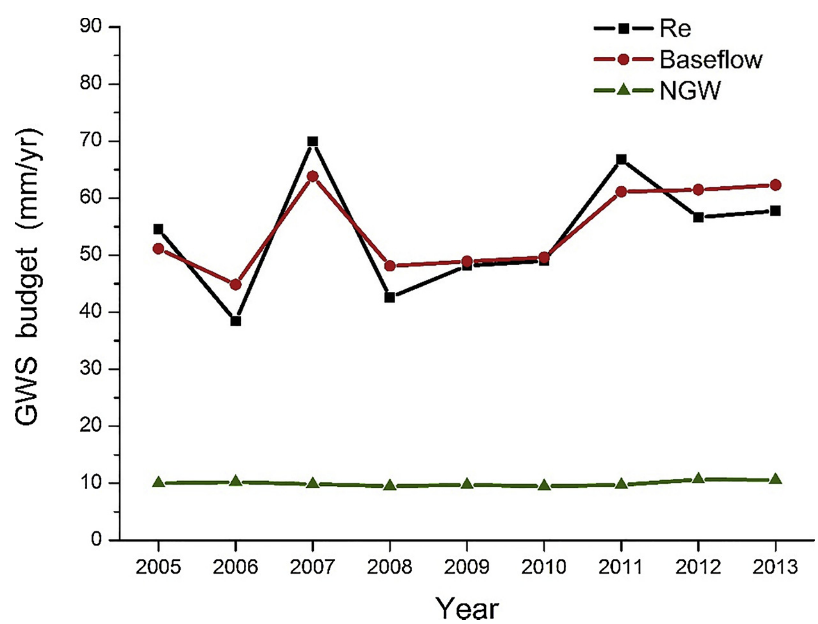

Fig. 7. Annual GWS budget including recharge (Re), baseflow and net groundwater withdraw (NGW).

from the water balance. Therefore, the natural recharge-discharge processes and groundwater abstraction continuously caused groundwater depletion. Please note that these yearly estimates of the *GWS* trend are slightly different from the monthly-based estimates as described in Subsection 3.2 because of data uncertainties and the timescale difference.

3.4. Groundwater consumption of different sectors

Although the total groundwater consumption by human activities was stable during 2005–2013, each groundwater consumption sector in the YRB had different contributions to the groundwater storage decline. In the YRB, there are four primary groundwater consumption sectors, including agricultural irrigation, industrial and domestic abstractions, and groundwater use for public services. Here, we further identify the contribution from each of the four sectors based on the data from the WRB-YRB.

Fig. 10 presents the groundwater use by each sector. Agricultural irrigation, accounting for 61.69% of the total groundwater abstraction, consumed the largest amount of groundwater among the four, followed

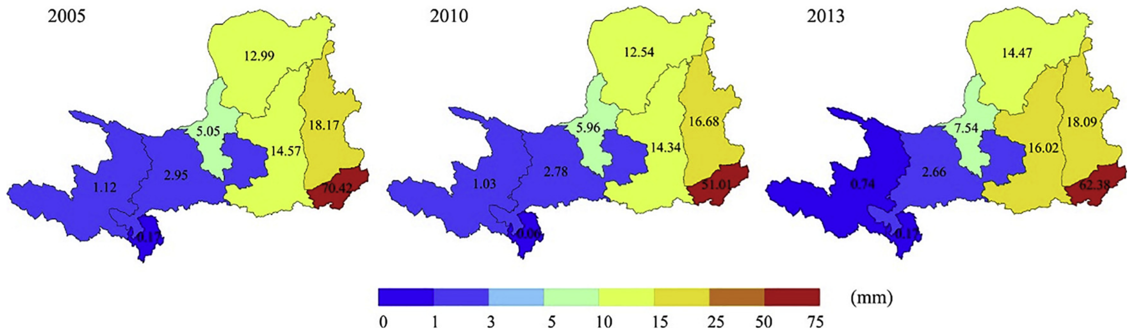

Fig. 8. The amount of groundwater withdraw of each province in YRB for three typical years, 2005, 2010, and 2013.

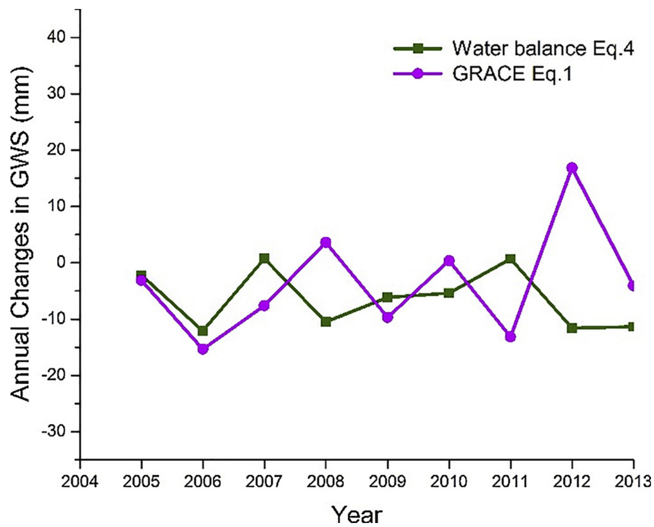

Fig. 9. Annual-scale changes in GWS derived from GRACE with Eq. (1) and water balance Eq. (4).

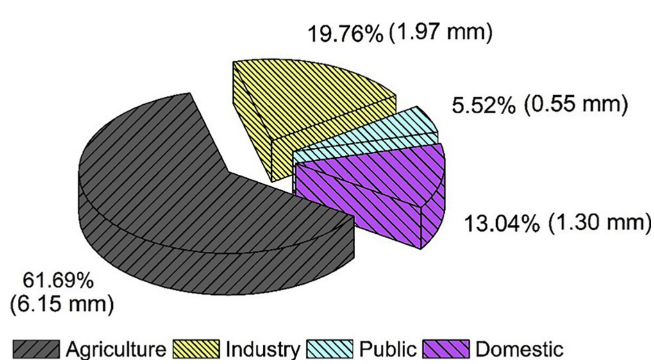

Fig. 10. Long-term average groundwater consumption of different sectors.

by the industrial sector (19.76%), the domestic sector (13.04%), and public (5.52%) consumption. The groundwater consumption by each sector has an obvious temporal variation as shown in Fig. 11. Specifically, the groundwater consumption for agricultural irrigation decreased significantly from 6.55 mm (50.78 km^3) in 2005 to 5.78 mm (44.89 km^3) in 2012. The other three sectors increased groundwater abstraction, and their total groundwater consumption increased 45%, from 3.45 mm (26.79 km^3) in 2005 to 4.86 mm (37.77 km^3) in 2012. The withdrawal by the industrial sector contributed the most to the increase, increasing from 1.80 mm (13.99 km^3) to 2.6 mm (20.15 km^3). Therefore, the amount of the groundwater consumption from the four sectors had a slight positive trend during the period.

4. Discussion

4.1. Contribution of human-nature impact

In this study, the GRACE data and in situ observations were used to detect the changes in terrestrial water storage and groundwater storage in the YRB. The two sources of data provided consistent estimates for the trend for groundwater storage of about −3 mm/yr for the YRB as a whole, with a significant decrease in *GWS* in the eastern part of the YRB. Similar estimates were also reported by other studies. For example, Zhao et al. (2015) indicated that the TWS in the eastern part (in Shanxi Province) had a downward trend of about –7.76 mm/yr with a notable *GWS* decline. In the southeastern part of the region, the GWS had the largest depletion (Feng et al., 2013). Our study presented a large-scale estimate for the groundwater storage change.

Human activities and climate had different contribution to the groundwater storage change, varying both temporally and spatially. The climate change impacted groundwater storage positively due to slight increased precipitation and groundwater recharge. Xie et al. (2015) also demonstrated the spatial and temporal variations of groundwater recharge in the YRB using a land surface modeling. However, this increased recharge was mostly offset by the trend of baseflow. The spatial variability of the groundwater withdrawal is consistent with the distribution of the groundwater storage decline. The eastern YRB, especially the south-eastern YRB, experienced the largest groundwater withdrawal, which significantly contributed to the groundwater storage decline in this area. Therefore, the change rate of GWS was dominated by the groundwater withdrawal for various uses.

Groundwater withdrawal was primarily used for agricultural irrigation in the YRB, as in many other regions in China (Yu et al., 2003; Taylor et al., 2013). However, the amount and the fraction of groundwater withdrawal for irrigation have been substantially reduced due to the shrinkage of crop land, since a few forestry ecological projects have been implemented in this region, e.g., the Grain for Green project that led to an increase in forest area (1845 km^2) and a reduction in crop plantation (−1984 km^2, −6.59% of the total crop land) (Wang et al., 2009; Xie et al., 2015). Unfortunately, this reduction of irrigation failed to reverse the groundwater storage decline, because the total groundwater withdrawal was relatively stable.

In contrast to agricultural irrigation, the industrial, domestic, and public withdrawals notably increased because of economic development in the YRB (Wang et al., 2017; Yin et al., 2017). Therefore, groundwater storage continued to decline with stable groundwater withdrawals. According to the groundwater budget analysis, moreover, the GRACE and the water balance equation provided evidence of the long time groundwater over-exploitation.

4.2. Implications for water resource management

The trend in groundwater storage and the contributions discussed above have implications for water resource management in YRB. Along

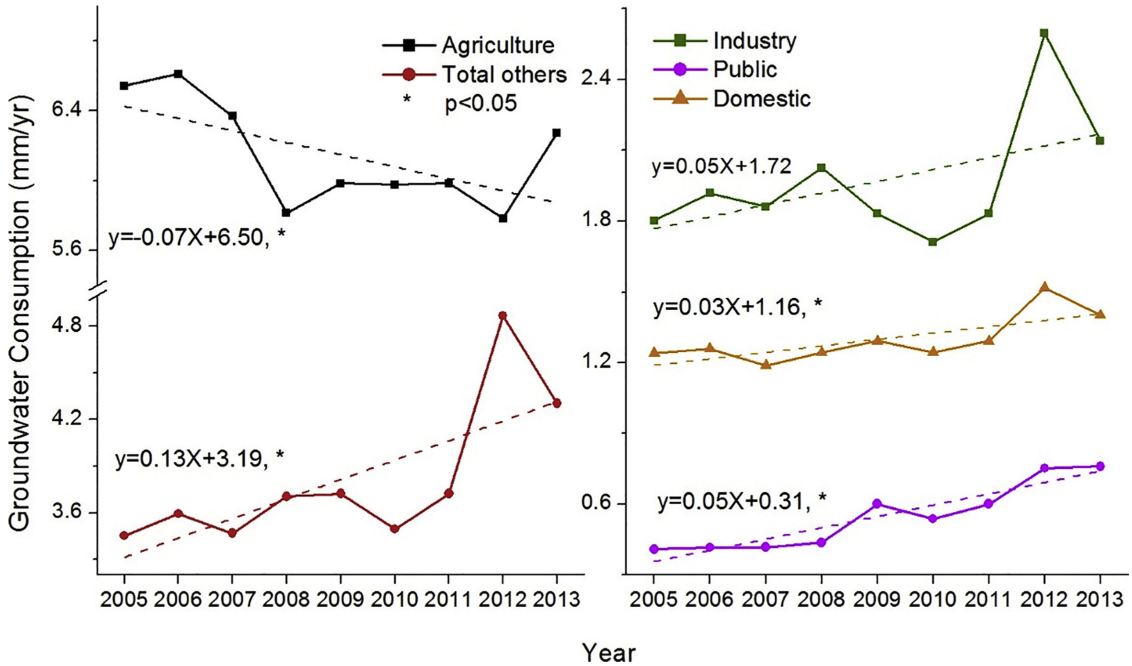

Fig. 11. Groundwater consumption in different sectors. The dashed line denotes the linear fit for related groundwater consumption series.

with an emphasis on ecological restoration, groundwater protection and recovery are of great concern in China. To relieve groundwater storage depletion, it is important to consider interactions among climate change, land surface and groundwater hydrology, Water Conservancy Engineering, and human social systems, including societal adaptations to water scarcity, to realize the sustainable development of water resources.

A few effective measures can be adopted to ease the groundwater loss, including artificial recharge of water into aquifers, crop structure adjustment, and water saving irrigation (Konikow and Kendy, 2005). Since agricultural irrigation is still the largest groundwater user among the four sectors, limiting water allocation for agricultural irrigation should be encouraged to ensure a sustainable level of water sue (Perry et al., 2017). Introducing effective irrigation techniques, such as drip irrigation and micro-sprinkle irrigation, can increase water use efficiency by more than 90% at field scale. In this sense, improving the irrigation mode in the YRB is able to reduce the dependence on groundwater. On the other hand, these hi-tech irrigation may encourage more crop planting and consequently cause more water allocation (Perry et al., 2017). Therefore, introducing hi-tech irrigation in absence of controls on water allocations will likely make the situation worse. To address such a paradox of irrigation efficiency, physical water accounts the farm-scale to the basin scale are needed for areas where the hi-tech irrigation is implemented (Grafton et al., 2018). Moreover, industrial water demands from the groundwater system could be relaxed to a certain degree by allowing for efficient water recycling. Ecological projects that were implemented in YRB, such as the Grain for Green, should be comprehensively evaluated for their effectiveness in groundwater recharge or discharge.

Water resource assessments could pay more attention to comprehensive strategies for surface water and groundwater allocation, considering the impact of climate change across the YRB (Luo et al., 2014; Yang et al., 2016). Moreover, economic measures should be used to encourage efficient use of water and reallocation of water among different sectors. The community should understand the fragility of the groundwater, and more specific goals, and a comprehensive management scheme should be developed for groundwater use.

4.3. Uncertainties and limitations

Despite consistent estimations for groundwater decline, our study was subject to uncertainties and limitations regarding the data and methods. First, only data from a nine-year period were used to analyze the groundwater pattern. Groundwater storage generally requires a long time period (> 20 years) to reach equilibrium under climate forcing and human disturbances (Döll et al., 2015). Therefore, the data length was deficient for reflecting the groundwater pattern. Second, the groundwater storage estimation from the ground observations had substantial uncertainty due to the spatial distribution of the wells. The regional groundwater storage was retrieved based on 54 wells, most of which are distributed near residences, and the observations may have been influenced by human impact. Groundwater withdrawals initially led to a decrease of stored groundwater volume within the cone of depression of hydraulic heads around the pumping well. Observation sites could detect this but may have exaggerated the pattern of GWS at a regional scale. Therefore, these data were only used to evaluate the GRACE derived groundwater storage, though the two approaches gave similar estimates for the trend in the groundwater storage. Third, the groundwater recharge estimates may have substantial uncertainties because they were computed from the VIC model simulation in which the groundwater component was not well formulated (Liang and Xie, 2001; Xie et al., 2015). And finally, our study focused on the quantity of the groundwater storage rather than the groundwater quality, which is also a serious concern in the YRB and the other basins in China (Jiang et al., 2008; Li et al., 2010; Su et al., 2009).

Despite the above mentioned uncertainties and limitations, our study provided a regional-scale evaluation of groundwater depletion and quantified the contribution of natural groundwater recharge and human withdrawals. Various sources of data including GRACE, land surface hydrological modeling, and in situ observations were used and they provided consistent estimations.

5. Conclusions

This study employed multi-source data sets to quantify the spatial and temporal pattern of groundwater storage in the YRB related to climate change and human activities. The results demonstrated that the

terrestrial water storage has substantially decreased at a rate of −2.33 mm/yr during 2005–2013. The pattern of groundwater storage was investigated based on GRACE and ground observations, and the two approaches gave consistent estimates for the trend, at about −3 mm/yr. A slight increase or stable state was observed in groundwater storage after 2011. Moreover, groundwater storage exhibited spatial variability, with a significant depletion in the southeastern part of the YRB where human activities regarding groundwater withdrawal were intensive.

The roles of climate change and human activities in the groundwater depletion varied during the period. Natural groundwater recharge was observed as a positive trend because of increased precipitation, especially in the northeastern area. However, the increased recharge was mostly offset by the baseflow. Therefore, groundwater storage decreased with human groundwater withdrawal. The total net groundwater withdrawal was nearly stable (about 10 mm/yr), although agricultural irrigation from groundwater decreased substantially partly due to the implementation of ecological projects in the YRB. The total withdrawals from other sectors, including industrial, public, and domestic consumption, increased 41% during 2005–2012. Particularly, industrial groundwater consumption, which accounted for 19.76% of total groundwater consumption, increased about 44%. Therefore, groundwater withdrawal still played a significant role in groundwater depletion.

There were a few uncertainties and limitations with respect to the length of the study period, data quality, and spatial representativeness of the ground observations. However, this study concluded that the sectors that account for groundwater depletion in the YRB have changed, and that it can support scientific decisions on water resource allocation and use in the YRB. Despite the decrease in the use of groundwater for irrigation, agricultural irrigation accounted for over 60% of groundwater use. Therefore, when emphasizing new techniques for agricultural irrigation (e.g., drip irrigation and micro-sprinkle irrigation), we should pay more attention on water allocations on the basis of basin and regional scale water accounting to avoid the paradox of irrigation efficiency (Perry et al., 2017; Grafton et al., 2018). A comprehensive management strategy for surface water and groundwater is important for the lower reaches (the southeastern area) of the YRB.

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